ESTCP
Cost and Performance Report

(WP-200907)

Demonstration of Heavy Diesel Hybrid Fleet Vehicles

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NAVFAC EXWC conducted demonstration validation testing on two heavy hybrid truck platforms. The first platform included a hybrid hydraulic refuse truck for curbside collection of recyclables. The second platform included a hybrid electric utility truck with an aerial lift system (i.e., bucket truck) for electric power line maintenance. The demonstration included a baseline evaluation at Aberdeen Proving Grounds, MD, followed by in-use operator testing at Bangor WA, and San Diego CA. The performance objectives included fuel economy, noise levels, brake wear, ease-of-use, maintainability, and drivability.

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COST & PERFORMANCE REPORT

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ACRONYMS AND ABBREVIATIONS

ATC	Aberdeen Test Center
CILCC	Combined International Local and Commuter Cycle
DOD	Department of Defense
EPA	Environmental Protection Agency
EPACT	Energy Policy Act
ESTCP	Environmental Security Technology Certification Program
HLA	Hybrid Launch Assist
IPT	Integrated Product Team
ISO	International Standards Organization
MPH	Miles per Hour
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NBK	Naval Base Kitsap
PTO	Power Take-Off

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The Environmental Security Technology Certification Program's (ESTCP) sponsorship for testing under this project catalyzed interest among the services' and enabled leveraged funding for the demonstration trucks. ESTCP also provided critical guidance and input on the demonstration plan and protocol for the validation effort.

Recognition is due the Army's Tank Automotive Research Development and Engineering Center and the Naval Facilities Engineering Command (NAVFAC) for purchasing the trucks, hosting the demonstrations, and providing data collection support during the demonstration. Also, NAVFAC Northwest and NAVFAC Southwest Base Support Vehicles and Equipment (BSVE), Solid Waste Management, and Coastal Utility Integrated Process Teams provided valuable feedback and insights on the truck operations and maintenance critical to the site validation testing.

Army's Aberdeen Test Center provided logistics and testing support for track testing at Aberdeen Proving Grounds. This included development of the test procedures, delivery of the trucks to and from Aberdeen, equipping trucks with test instrumentation, and coordinating with the manufacturers and NAVFAC Engineering and Expeditionary Warfare Center (EXWC), and execution of the track testing.

Importantly CALSTART, through the High-Efficiency Truck User Forum, established a working group for non-tactical fleets that facilitated a partnership with the manufacturers. This partnership enabled sharing of information to promote a successful demonstration. CALSTART also procured the hybrid utility truck, contributed logistical support, and managed the on-board data collection effort during the site testing effort.

Project success and accomplishment is owed to the suppliers of the truck chassis, hybrid systems, and body without which the project would not have been possible. The suppliers provided special on-site support and assistance for scheduling truck deliveries to the test sites and for equipping trucks with data collection instrumentation for all testing. Suppliers also provided extensive support for the track and site testing throughout the demonstration.

The Navy's Environmental Program provided fundamental project support. The Navy's Environmental Sustainable Development to Integration program provided initial leveraged funding for project development. NAVFAC EXWC provided guidance for conceptual project planning, test plan development, and technology integration objectives. In addition, NAVFAC EXWC's Environmental Technology team provided assistance with project logistics, scheduling, and test execution.

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EXECUTIVE SUMMARY

Environmental Security Technology Certification Program Office awarded funds for a project to demonstrate heavy diesel hybrid trucks for non-tactical fleet applications. Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) provided overall coordination for testing execution. Test objective was to evaluate cost and performance benefits of two primary types of heavy hybrid platforms for Department of Defense (DOD) Public Works applications.

NAVFAC EXWC demonstrated two commercial hybrid power train technologies as potential solutions to mitigate environmental and energy impacts of conventional diesel powered trucks. Current diesel trucks are noisy, polluting, and large consumers of fossil fuel. Hybrid power systems help mitigate these problems by capturing and reusing energy that is normally wasted on braking. This captured energy is used to power launch assist and engine-off work applications, all while significantly reducing brake use.

The project team purchased and deployed four test trucks for the demonstration, including one pair of refuse trucks and one pair of utility trucks. Each test pair included a conventional truck baseline, and a hybrid truck of equivalent make, model year, and production run. Refuse trucks were built on a refuse truck chassis, with four individual troughs and side loaders for collection of separated recyclables. Utility trucks are based on a utility truck platform, and an aerial lift body to support utility line maintenance. The hybrid equipped utility truck is an electric configuration with battery storage, regenerative braking, launch assist, and engine-off power.

Test applications for each truck pair are common to the DOD. The refuse truck application is representative of pickup and delivery applications. The utility truck application is representative of stationary work applications requiring on-board power. Both applications show potential for broad integration across the DOD non-tactical vehicle fleet, and provide opportunities for fuel economy and noise reduction benefits.

Validation efforts included both track and site testing. Track testing provided baseline data using controlled drive cycles for reference evaluation of fuel economy and noise profiles. For site testing, host sites integrated the trucks into their routine operations for evaluation of drivability, maintainability, reliability, and ease-of-use. Track test procedures were designed for objective evaluation of performance criteria. Site testing relied heavily on feedback from the truck operation and service teams with emphasis on qualitative performance.

Fuel economy test results were similar for both track and site testing. Hybrid refuse truck showed no fuel economy improvement for either the track or site testing. This appeared due to the mild driving cycles with minimal start and stops. Hybrid utility truck demonstrated an improvement in fuel economy for both the track and site testing. Track test results showed a 75 percent higher fuel economy for the DOD Test Cycle, and a 15 percent improvement for the Combined International Local Commuter Cycle drive cycle. The hybrid utility truck's overall fuel economy improvement for site test was 32 percent.

The project team conducted noise testing at Aberdeen Proving Grounds Maryland track and road facilities. Aberdeen Test Center provided truck operators and NAVFAC EXWC measured idling

and acceleration noise using hand-held sound pressure meters. Both hybrid technologies were partially effective at reducing noise, depending on location and operational mode. Hybrid trucks reduced in-cabin noise levels by 40 percent for acceleration events. When idling, the hybrid utility truck offered a 50 to 80 percent noise reduction. Hybrid in-cabin noise was higher for deceleration and steady speed modes. Both hybrid trucks had higher outdoor noise levels than the baseline trucks for acceleration and deceleration modes.

Site testing was generally positive for both truck pairs. Neither hybrid system required maintenance during the demonstration period. Also, there were no symptoms or issues that suggested the hybrid systems would become a future maintenance liability. Both hybrid hydraulic and hybrid electric platforms showed 63 and 23 percent less brake wear than their conventional counterparts, respectively. Both hybrid trucks met ease of use objective that indicates the level of training required. The hybrid electric truck required attention to engine and transmission settings.

In terms of performance acceptance the hybrid refuse truck failed to meet the critical performance objectives for fuel economy. This result is not associated with the hybrid system itself, but due to the mild driving cycle typical of most non-tactical truck applications on DOD facilities. If placed in a severe duty cycle, further consideration is warranted, however it does not appear the DOD has a significant number of related applications. The project team concluded the hybrid system tested is not compatible with most DOD duty cycles.

The hybrid utility truck successfully achieved four of six performance acceptance parameters, including fuel economy, noise, maintainability, and ease of use. The truck fell short of the drivability and brake wear objectives. The project team assumes drivability and brake wear will improve with further engineering and software optimization. Hybrid electric utility truck is considered acceptable by the project team, with the caveat that procurement officials ensure minimum acceptance requirements carefully match the truck application.

Based on the validation test results, the hybrid electric utility truck will be cost effective for future scenarios involving moderate driving (i.e., 7,000 miles per year) and high use of the power take-off system (i.e., 3 hours daily). DOD applications meeting the criteria will realize cost benefits from the technology's efficiency and quiet operation. Simple payback will occur over a 12-year life cycle assuming the above scenario. The assumptions include a $37,000 premium for the hybrid truck, initial operation and maintenance training for $3,000, and a battery replacement at $5,000. All benefits are direct with the exception of greenhouse gas emission reductions. The greenhouse gas emission reductions benefit DOD by reducing the impacts related to global warming. An additional indirect benefit for DOD is improved National energy security and reduced petroleum dependence.

Hybrid hydraulic refuse truck would not achieve simple payback for the mild drive cycle common to DOD applications. The target duty cycle application for a cost savings includes frequent and abrupt stops and starts. A hypothetical scenario where the hybrid hydraulic truck would be cost effective includes six hours of daily use at low average speeds and multiple stops. The duty cycle assumes a 7,500 mile annual mileage, a $30,000 cost premium for the hybrid system, and $5 per gallon for petroleum diesel. This scenario would realize simple payback assuming a 20 percent efficiency improvement. Savings over a 12-year life cycle include avoided fuel payments

($23,333), reduced labor for fueling events ($3,967), avoided brake service events ($1,650), and fewer greenhouse gas impacts ($1,400). Under this scenario, return on investment is approximately $4/mile for every mile above 90,000 miles.

While the environmental benefits are proven, return on investment requires that agency planners and procurement officials take the following steps: 1) characterize heavy truck inventory subject to high use or abusive cycles; and 2) pair hybrid technology and application sets promising the greatest benefit. Planners develop an agency replacement plan in coordination with agency fleet managers. Close coordination among planners, fleet managers, and procurement officials will help ensure hybrid truck procurements result in the maximum benefit.

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1.0 INTRODUCTION

The Department of Defense (DOD) has a large fleet of diesel powered vehicles and equipment (e.g., utility service trucks, stake trucks, delivery vans, and material handling equipment). Most of this equipment is operated under stressful, intermittent, and varying load conditions. For a conventional vehicle, these duty cycles make engine operations inefficient and increase fuel consumption and carbon dioxide (CO_2) emissions. Hybrid technologies reduce these problems by allowing for smaller engines that operate under more steady rpm and load conditions, while recovering the energy normally wasted from braking. Fuel usage is reduced, air standards are met, and noise pollution and safety are improved. Given these advantages, DOD transportation planners are interested in the viability of hybrids for both domestic public works operations, and forward-deployed settings.

1.1 BACKGROUND

NAVFAC EXWC demonstrated two commercial hybrid power train technologies as potential solutions to mitigate impacts of heavy trucks on the environment and on energy security. The hybrid technologies reduce fuel use by recovering energy normally wasted to heat during braking, and then reusing that energy for launch assist and for work applications.

Fielded systems included an aerial lift truck and refuse hauler. The project team conducted baseline testing and subsequently placed the test vehicles at supportive sites with an operational requirement for these vehicles. Monitored parameters included fuel economy, noise levels, unscheduled maintenance issues, vehicle availability, vehicle reliability and any impacts to day-to-day operations, as well as impacts to overall mission readiness. The team conducted the validation assessments to determine how the hybrid vehicles could meet operational performance goals, including accelerations, stops, auxiliary system functioning (i.e., equivalent lifting, loading, and cargo handling capacity).

1.2 OBJECTIVE OF THE DEMONSTRATION

This project achieved two primary objected, including 1) evaluate benefits and readiness of existing early-commercial hybrid platforms, and 2) establish a military link to the hybrid vehicle manufacturing industry.

1.3 REGULATORY DRIVERS

Public and scientific environmental awareness and concern surrounding the combustion of fossil fuels and resulting greenhouse gases, criteria gas pollutants, and particulate matter is forcing regulatory agencies to impose more stringent standards and regulations for energy efficiency. Executive Order 13423, Energy Policy Act of 1992, and National Defense Authorization Act of 2008 established metrics that challenge agencies to operate fleet vehicles more fuel efficiently.

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2.0 TECHNOLOGY

Emerging heavy hybrid electric vehicle technologies feature a supplemental power system that substantially improves efficiency. Similar to light duty hybrids, heavy systems recover the energy normally wasted during braking operations. Hybrid systems supplement the conventional engine during peak power demands (accelerations, hill climbing, lifting, drilling, excavating, etc.). Use of regenerative braking also reduces maintenance required on braking systems. The following sections will go into detail about heavy hybrid technology.

2.1 TECHNOLOGY DESCRIPTION

Heavy duty hybrid vehicles feature a supplemental power system for the diesel internal combustion engine. The supplemental system is typically either electric or hydraulic. With an electric hybrid, braking (kinetic) energy is captured by using the propulsion system to apply a load to the drive axle during braking, and converted into electrical energy via a generator, as shown in Figure 2-1. The vehicle stores that energy in on-board batteries for driving the wheels at another time. Hydraulic hybrids are similar in approach, except that they store braking energy with high pressure accumulators that assist with vehicle propulsion when needed, as shown by the diagram in Figure 2-2. These systems avoid the requirement for large battery systems and complex electrical controls.

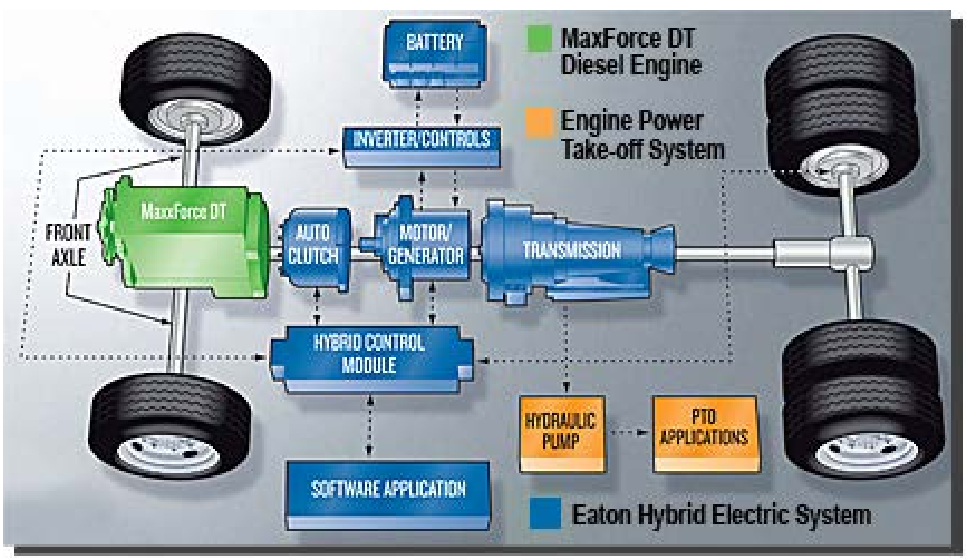

Figure 2-1. Diagram of Hybrid Electric System.

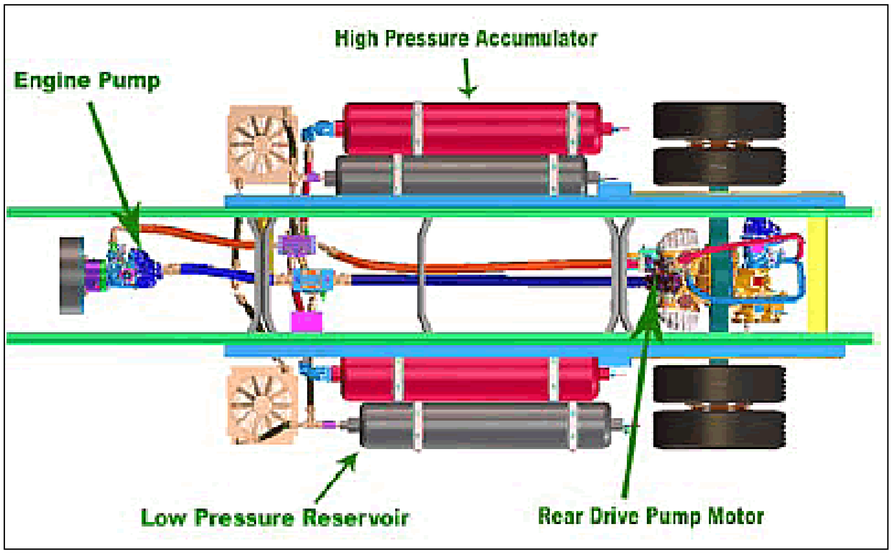

Figure 2-2. Diagram of Hydraulic Hybrid System.

The high pressure accumulator stores energy as a battery would in a hybrid electric vehicle.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLGY

Diesel hybrids will provide direct benefits to the vehicle owner and operators. For DOD, hybrids will benefit not only domestic public works vehicle applications, but also deployed vehicle operations. Hybrids provide better vehicle performance, reduced engine size and footprint, reduced environmental impact, and improved range for remote operations. Hybrid systems enable manufacturers to optimize diesel engines for lower and steadier loads. This dramatically decreases emissions, fuel use, and noise in high load situations. Electrification further improves efficiency, response-time, and precision of traditional belt-driven systems. Heavy vehicle platform benefits include smaller engines, smaller after-exhaust particulate filters, and electrification of auxiliary equipment, which could further reduce operating costs and enhance performance.

For certain applications and truck configurations, the hybrid energy storage systems will impact truck capacities and performance to the extent that daily operations are also impacted. If the duty cycle requires that the truck to be fully loaded with cargo, the hybrid could impact the daily operations (e.g., extending the daily operating cycle for the refuse operators). Fleet managers and procurement officials can address these limitations by defining minimum capacity requirements during the procurement process.

3.0 PERFORMANCE OBJECTIVES

This project evaluated the benefits and readiness of existing early-commercial hybrid platforms, and established a military link to the hybrid vehicle manufacturing industry. The project further identified platforms that would benefit most from the hybrid technology. Table 3-1 and Table 3-2 below describe in detail both the quantitative and qualitative performance objectives.

Table 3-1. Performance Objectives – Refuse Trucks

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Fuel Economy – Track Testing – Site Testing	• Controlled Drive Cycle Fuel Economy Test • Transaction Logs, On-Board Computer Data	• >20% Increase Fuel Economy	• Did not meet Objective • Track: 13% Decrease • Site: No Significant difference
Noise Levels – In-Cabin Noise Levels – External Engine Noise	• FMCSA Part 393.94 • Exterior: 10 Ft Away, 25 Ft from Centerline	• >20% Peak (dBA) Noise Reduction for Accelerations	• Did not meet objective • In-Cabin: 39% Decrease • Exterior: 20% Increase
Brake Wear	• Measure Brake Lining Thickness Initially and at Six Months	• >50% Reduction in Brake Wear	• Met objective • Achieved
Maintainability	• Interviews with Fleet Manager • Maintenance Logs – Downtime for Troubleshooting or Repairs – Time In Shop – Parts Failures • Inspection Records	• No Major Failures • ≤2 Minor Parts Failures • ≤1 Week Downtime for Unanticipated Service • ≤1 Additional hour of Service • No Service or Maintenance Complaints	• Met objective • No hybrid system or parts failures • Extensive downtime to resolve trough loader operational issues • No additional hybrid related service required during the testing period • No hybrid related service complaints
Qualitative Performance Objectives			
Drivability	• Accelerator Pedal Position • Driver Survey • Telematics Data	• No Excessive Accelerator Position • Comparable Approval Ratings by Users • Comparable Operation of Utility Bucket, Refuse Lift • Sufficient Power Under Heavy Loads and at Low Speeds	• Met objective • Operators reported excellent power and drivability performance • HLA equipped unit provided superior power to the baseline truck • Operators noted issue with strong regenerative braking on HLA truck
Ease of use	• Survey and feedback data from operators and fleet managers on usability of trucks and training / adjustment time	• ≤2 Hours operator training required • ≤10 hours Driver Adaptation Time	• Met objective • 1-Hour of Driver Training plus Adaptation was Sufficient

Table 3-2. Performance Objectives – Utility Trucks

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Fuel Economy – Control (Track) Testing – Site Testing	• Controlled Test Cycle • Fuel Transaction Logs, On-Board Computer Data	• >20% Increase Fuel Economy	• Met Objective • Track: 75% and 15% increase for DOD Cycle, CILLC Cycles) • Site: 32% increase
Noise Levels – In-Cabin Noise Levels – External Engine Noise	• FMCSA Part 393.94 • Exterior: 10 Ft Away, 25 Ft from Centerline	• >20% Peak (dBA) Noise Reduction for Low Speeds, Static	• Missed Objective for outdoor drive-by tests; • In-Cabin: 39%-49% decrease • External: 77%-83% decrease for PTO; 12%-55% increase for drive-by tests
Brake Wear	• Measure Brake Lining Thickness Initially and at 6-Months	• >50% Reduction in Brake Wear	• Did not meet objective • 36 percent reduction in brake wear.
Maintainability	• Interviews with Fleet Manager • Maintenance Logs – Downtime for Service, Repairs – Time In Shop – Parts Failures • Inspection Records	• No Major Failures • ≤2 Minor Failures • ≤1 Week Downtime, Unanticipated Service • ≤1 Additional hour of Service • No Service Related Complaints	• Met Objective • No major System Failures • No Minor Parts Failures • Zero Days Downtime due to Hybrid System • No hybrid Related Service Required
Qualitative Performance Objectives			
Drivability	• Accelerator Pedal Position • Driver Survey • Telematics Data	• No Excessive Accelerator Position • Comparable Approval Ratings by Users • Comparable Operation of Utility, Refuse Lift • Sufficient Power Under Heavy Loads and at Low Speeds	• Did not meet Objective • operators reported lack of power for accelerations, excessive shifting on hilly terrain
Ease of use	• Survey operators and fleet managers on drivability, training / adaptation time	• ≤2 Hours operator training required • ≤10 hours Driver Adaptation Time	• Met Objective • 1-hour training and 4-6 hours adaptation time sufficient.

Performance objectives are based on user defined requirements and environmental benefits either sought or claimed by the hybrid truck industry. The following includes an explanation, description, and success criteria.

Fuel Economy. This objective is the fundamental benefit sought by the industry and the fleet users, and is critical to the success of hybrid industry. Fuel economy gains will help the fleet owners justify upfront investments in the hybrid technology. If the technology fails to meet this objective, the customers will not see a return on the hybrids' initial cost premium.

Metric for the vehicles can be expressed in different ways depending on the type of use or duty cycle. For refuse trucks, or vehicles whose work mode is predominantly driving, units are miles per gallon (mpg). For the utility trucks, or vehicles whose primary application involves engine off work, units are in terms of gallons per hour (gph).

Success criteria include a 20 percent improvement in fuel economy (minimum) over the conventional trucks. This is the benefit sought as an initial objective, depending on the duty cycle. Units for the metric depend on the application as noted above.

The hybrid utility truck achieved the success for the fuel economy objective for the intended use pattern (i.e., 80 percent lifting, 20 percent driving) demonstrated on the track. It also achieved the objective for the site testing.

The project team attributes this to a mild drive cycle that does not take advantage of the hybrid's regenerative braking and launch assist features. The hybrid refuse truck fell short of the fuel economy objective for both the track and site testing.

Noise Levels. This includes both in-cabin and exterior engine noise affecting the driver and persons in the immediate area, respectively. This includes nuisance noise with potential to disturb nearby residents or personnel and disruptive noise that interferes with communications among the work crew. Either type of noise limits productivity and reduces quality of work or life for base personnel (i.e., employees or residents).

Noise measurement is in terms of A-weighted decibels. The A-weighted scale is selected to best characterize noise levels perceived by humans. A-weighting helps compensate and adjust levels based on frequency variation. Humans perceive noise as being louder or more offensive at the higher frequencies. This is also the range that results in damage to the audible mechanism.

The 20 percent criterion is based on the assumption that the hybrid system provides a moderate reduction in engine load and resultant peak noise levels. This project established a 20 percent reduction as an initial objective for the technology. This assumes that the noise will decrease further with additional engineering and development.

The hybrid refuse truck fell short of the objective noise reduction criterion. Hydraulic hybrid system reduced in-cabin noise, but increased outdoor noise a primary objective for this demonstration. Overall peak noise levels increased by 20 percent for the hybrid truck.

The hybrid electric utility truck achieved an 80 percent reduction for the primary mode of interest, including the power take-off (PTO) mode for work operations. This addresses both interference with crew communications, and annoyance noise impacts to the surrounding public. As such, the hybrid truck is considered to have successfully met this objective.

Brake Wear. Use and replacement of brakes is a significant maintenance expense on severe duty trucks. Brake wear is an indicator of avoided brake use relative to baseline truck operation. The metric (i.e., 50 percent reduction in brake wear) reflects truck manufacturer claims that hybrid system can extend replacement cycle double to quadruple the baseline.

The refuse truck met performance acceptance objective for brake wear. When engaged, the hydraulic launch assist unit offsets brake use. Under actual use conditions, the hydraulic launch assist (HLA) disengages at speeds in excess of 20 mph and will incur related brake wear. Despite higher speed use during site testing, the truck still met the 50 percent objective. If matched with the appropriate application, the HLA would result in a more significant reduction in brake wear.

Normalized brake wear on the hybrid utility truck was 3.58 inches per 100,000 miles, as compared with 3.58 inches for the conventional truck. This is a 36 percent wear rate reduction for the hybrid truck, short of the 50 percent performance objective. Differences in driving habits or duty cycle are a potential source of bias. Manufacturer adjustments to the regenerative braking system could reduce the wear rate.

Maintainability. Preventative maintenance for new technologies must be comparable to the existing platforms. Technologies that require a high level of effort to maintain suggests greater downtime, higher operating costs, and user frustration, which ultimately leads to failure.

The project team used feedback from the service team and maintenance records to evaluate whether the trucks met the maintainability criteria. To meet the criteria, the trucks must not have incurred any substantial maintenance or downtime. This includes less than two minor service events, no major component failures, less than one-week of downtime (for hybrid related failures), and no related complaints from the fleet manager or service team.

Drivability. This factor is critical to the success of the new technology. In broad terms, this is how well the truck performs (i.e., whether driving or operating) relative to the baseline truck. Characteristics captured under drivability include acceleration, hill-climbing ability, cornering, lifting, controlling, starting, stopping, and ride quality.

This parameter is evaluated through response to the driver's application of the accelerator pedal, brake pedals, and lift controls. Given the subjective nature of the data, the project has established baseline trucks to increase objectivity.

To have acceptable drivability, trucks must offer sufficient power to accelerate under heavy loads and low speed conditions. Routine operation should not require excessive accelerator position to achieve the desired results. To succeed, trucks must receive comparable approval ratings by users for both driving and for work modes of the utility and refuse lift systems.

Ease of Use. This acceptance factor is qualitative and measures complexity and/or operator's time to adapt to the new operating procedure. Ideally the operations will be comparable to the existing technology, transparent to the user, and requires no additional training. Technologies with complex operating procedures require additional training, reduce flexibility to switch operators, and have potential to reduce productive time in the field depending on complexity.

Selected ease-of-use threshold level is two hours of training, and 10 hours of adjustment time. It is the intent of the project team that this criterion correspond to the training investment required to learn and adapt to operating controls for new truck models. As such, the hybrid technology should be transparent in terms of time to become acquainted.

4.0 SITES/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

The Naval Base Kitsap (NBK) Recycling Team collects solid waste media with conventional diesel trucks. Trucks serve facilities throughout the Bangor, Bremerton, Keyport, and Indian Island installations. Conventional diesel engines are powerful, but the older engines can pollute several times more than model year 2007 and newer engines. In addition to the hydraulic launch assist, the new refuse trucks will collect and maintain curb-separated recyclables, reducing labor associated with post-separation of plastic, paper, and metal.

NAVFAC Southwest utility truck fleet consists of conventional diesel trucks. Trucks have aerial lift platforms that have “buckets” that hold one or two personnel conducting the line maintenance. Two trucks are due for replacement and the team is interested in potential benefits of the hybrid platform. The team will purchase two replacement units, one conventional diesel truck and one diesel hybrid electric truck. Both new trucks will be of the same truck model with 50-foot telescoping and articulating lifts.

4.2 PRESENT OPERATIONS

At NBK, the refuse trucks average 14,000 to 18,000 miles per year. They operate on a regular five day work schedule and support additional collection runs on the weekend as needed. The diesel engines not only provide power to move the truck, but also power a hydraulic pump that operates the collection arm and lifts the bin. Engine “revving” occurs at stops to operate the hydraulic collect arm and container lift mechanism. As the truck becomes loaded, accelerations increasingly burden the engine and stopping results greater brake wear.

NAVFAC Southwest utility team operates aerial lift trucks for maintenance of electric power lines throughout the metropolitan San Diego Area. Trucks operate five to six days per week, with 35 to 50 hours of field time. Although trucks operate all day, most of the time they remain stopped. Daily driving averages only 35 miles. The engine is typically in an idle mode, powering the hydraulic system while the crews perform maintenance.

4.3 SITE-RELATED PERMITS AND REGULATIONS

With the exception of slightly different operating and maintenance considerations for the auxiliary power system, hybrid vehicles are virtually transparent to existing operations. No environmental permits are required to proceed with the demonstration.

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

5.1.1 Test Vehicles

The project team selected test vehicles to ensure a valid comparison. The hybrid and non-hybrid trucks were both new, of the same manufacturer model year, and included the same options. This prevented non-hybrid related performance variations due to engine or exhaust technology, aerodynamics, tires, or vehicle wear. Table 5-1 lists features of the vehicles, engines, and auxiliary systems. Figures 5-1 and 5-2 show each chassis type tested. Section 5.2 describes the hybrid systems in further detail.

Figure 5-1. Photo of Hybrid Hydraulic Refuse Truck.

Table 5-1. Test Vehicle Specifications

Utility Trucks	
Chassis	33,000 gross vehicle weight, 177 inch wheelbase
Utility System	50-foot Aerial Lift, Continuous Rotation and Tilt, Hydraulic Tool Circuits
Refuse Trucks	
Chassis	37,600 gross vehicle weight, 191 inch wheelbase
Refuse System	Curbside Recycler, Four Bins : 28.45 cubic yard total capacity, plus Individual Side Loader for Each Bin

Figure 5-2. Photo of Hybrid Electric Utility Truck.

5.1.2 Test Locations

Aberdeen Test Center (ATC), MD:

ATC conducted track testing at Aberdeen Proving Ground MD. ATC has several tracks with both paved and off-road tracks with engineered slopes, hills, and surfaces for vehicle testing. The project team selected and tested the trucks on a three-mile straight track in the Perryman Test Area. This track is flat and paved, and is representative of the generally flat paved roads on the industrial and administrative areas of military installations.

Naval Base Kitsap:

Consolidated in 2004, NBK consists of the three separate installations: Bangor, Bremerton, and Keyport. Bangor covers 7,201 acres, and is the largest of the three while Keyport and Bremerton are much smaller at 340 and 419 acres, respectively. Terrain at Bangor ranges from flat to moderate rolling hills, while Bremerton and Keyport are primarily flat. NAVFAC Northwest's Integrated Waste Management Team oversees NBK's waste collection program. Trucks collect mixed curbside recyclables, but are aspiring for curbside separation to enhance efficiency and reduce operating labor.

San Diego Naval Complex

NAVFAC Southwest Utilities Integrated Process Team is based in San Diego, California. The team serves naval installations throughout the metropolitan San Diego area. Beyond work at Naval Station San Diego, work sites include Coronado, Imperial Beach, North Island, and Point Loma. These facilities range from 5 to 22 miles apart. Roads at each installation are generally paved and flat. The Integrated Process Team dispatches trucks daily to the installations in order to accomplish a variety of power line maintenance tasks.

5.1.3 Schedule

ATC conducted track testing soon after delivery of the new truck pairs. Track testing schedule and execution was according to the test plan, occurring from October 2010 through January 2011. Site testing at NBK Bangor experienced severe delays, commencing February 2012, or 10 months behind the objective test schedule. Delays at NBK Bangor were due to side loader compatibility issues with the tote containers. Considering both locations, site testing extended the overall schedule by approximately 14 months with the data assessment.

5.2 TECHNOLOGY DESCRIPTION

One truck from each test pair includes a hybrid power system. One refuse truck is equipped with a hybrid hydraulic system, and one utility truck is equipped with a hybrid electric system. The parallel hybrid electric system provides launch assist, regenerative braking, engine-off electric power, and engine-off hydraulic system operation. Table 5-2 provides specifications for the hybrid electric and hybrid hydraulic systems.

Table 5-2. Hybrid Drive System Specifications

Feature	Specification
Hybrid Electric System	
Weight (hybrid drive unit, clutch, batteries, hardware)	980 lbs. (444.52 kg)
Battery	Nominal 340 Volts Direct Current / Lithium Ion
Electric Motor	44 kW peak, 60 hp/308 lb-ft. torque (420 Nm); 26 kW continuous, 35 hp/186 lb-ft. torque (252 Nm)
Hybrid Hydraulic System	
Weight	1,250 lbs.
Torque	2,550 ft-lb max
Active Speed Range	Up to 25 mph

5.3 TRACK TESTING DESCRIPTION

The Army's ATC accomplished outdoor track testing at Aberdeen Proving Grounds, MD facilities. Certified test personnel ran the vehicles at the selected track using specific operating cycles to measure fuel economy, noise levels, and other performance data.

5.3.1 Test Methods Description

5.3.1.1 Drive Cycles Description

Test cycle for the refuse truck is a modified version of the first 30 minutes of the Combined International Local Commuter Cycle. This cycle is a common test cycle for pickup and delivery truck applications. This scenario assumes the trucks collect three full loads of recyclables over a one-day period. Fuel economy results for this cycle are more conservative than for the severe residential cycle. Figure 5-3 illustrates the cycle speed versus time plot.

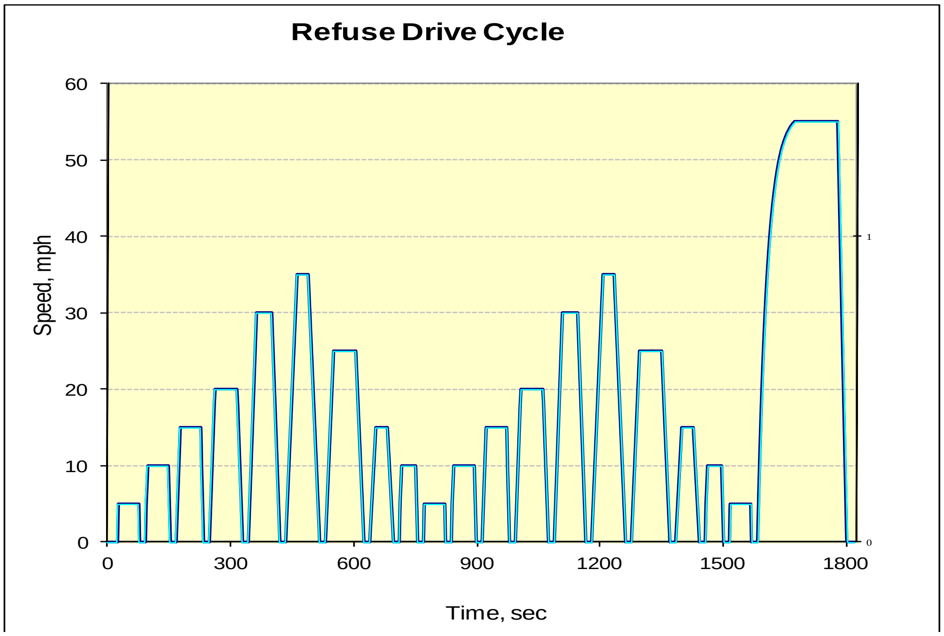

Figure 5-3. DOD Drive Cycle for Refuse Trucks

The utility truck cycle models a 6-minute trip to the job site, 45 minutes of field work using the aerial lift, followed by a return 6-minute trip to the utility team's central shop. Figure 5-4 shows the vehicle speed and the aerial lift height versus time plot. Driving constitutes 20 percent of the truck use during application, and field work accounts for the 80 percent balance.

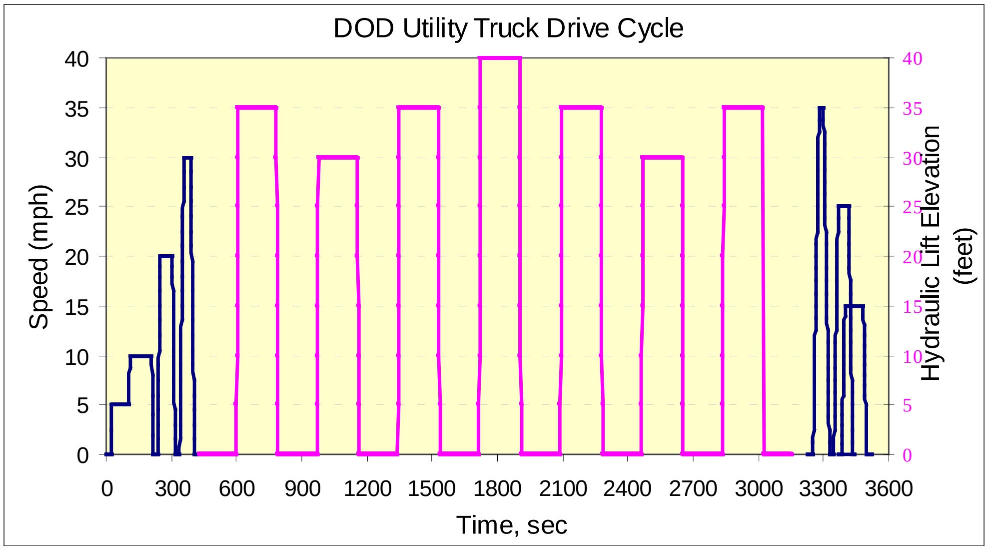

Figure 5-4. DOD Test Cycle for Utility Trucks

5.3.1.2 Fuel Economy Description

ATC installed a fuel metering system in order to record fuel flow throughout the testing. The metering method improves logistics of testing as compared with a portable fuel tank.

5.3.1.3 Noise Testing Description

NAVFAC EXWC personnel observed industry test methods for the sound level measurements. Measurements characterized noise inside the driver's cabin and outside the truck, in order to assess noise reduction benefits for the driver and the public. Table 5-3 provides standards observed for the sound level measurements.

Table 5-3. Industry Guidelines for Noise Sampling Locations

Noise Location & Type	Receptor	Microphone Locations	Reference Method
Indoor Engine Noise	Driver	Truck Cabin, 6-inches from Driver's Right Ear	FMCSA 393.94
Outdoor Acceleration	Bystanders	25-Feet from the Centerline of Travel, Both Driver and Passenger Sides of Truck	ISO 362-1:2007
Outdoor Engine & Lift System	Utility Workers, Bystanders	10 feet from the Driver and Passenger Sides of the Truck; 25 feet from the Truck Centerline.	ISO 362-1:2007

5.4 SITE TESTING DESCRIPTION

After track testing, each pair of trucks shipped to corresponding host sites for six-months of real-world testing. Demonstrations followed similar procedures at both sites, with variations in the application and data parameters of interest. Site testing began with kick-off meetings at both locations. The meetings included a baseline inspection, manufacturer training, and review of data collection objectives. Site testing included the following data collection methods:

- Fuel Logs/Operator Surveys
- Maintenance Data
- Automated Data

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6.0 PERFORMANCE ASSESSMENT

6.1 TRACK TESTING ASSESSMENT

Sections 6.1.1 and 6.1.2 cover results of the fuel economy and noise testing, respectively.

6.1.1 Refuse truck Fuel Economy

The Army's ATC conducted fuel economy testing on the conventional and hybrid refuse trucks. ATC accomplished a total of five acceptable drive cycle trials for both the conventional and the hybrid truck. Figure 6-1 shows the fuel economy testing in-progress.

Figure 6-1. Photo of Conventional Refuse Truck (foreground) with Mobile Data Acquisition System (MDAS) Trailer in the Background

Table 6-1 summarizes results of fuel economy testing. Of note, the measured conventional refuse truck economy was 13 percent higher than the hybrid truck. ATC's test driver noted the hybrid truck's strong regenerative braking effect slowed the truck to below the prescribed cycle speed. The operator applied the accelerator during coasting events in order to follow test protocol speed.

Table 6-1. Refuse truck Fuel Economy Results for Alternative Operating Modes

Platform Mode	DOD Cycle (mpg)	Change from Baseline	Test Objective	Met Objective?
Conventional (Baseline)	5.4	Baseline	Baseline	Baseline
Hybrid (Economy)	4.7	-13%		No
Hybrid (Performance)	4.7	-13%	20% Increase	No
Hybrid (HLA Off)	5.1	-6%		No

ATC applied statistical analysis to the fuel economy data to confirm significance of the results for the refuse truck economy testing. Table 6-2 presents a summary of the analysis. None of the 99 percent confidence values overlapped, confirming the statistical significance of the results.

Table 6-2. Statistical Analysis Results for the Refuse Truck Testing

	PARAMETER	CONVENTIONAL	HYBRID
CILCC Cycle	Average Economy Value (mpg)	5.4	4.7
	Standard Deviation	0.1	0.1
	99% Confidence Lower Limit	5.2	4.6
	99% Confidence Upper Limit	5.6	4.9

6.1.2 Utility Truck Fuel Economy

Table 6-3 summarizes fuel economy results for both test cycles. The hybrid truck meets the performance objective for DOD's lift cycle, but falls below the objective if the truck is used solely for driving. The drive cycle will be more severe than applications on small DOD installations with low speed driving and fewer stops.

Table 6-3. Utility Truck Fuel Economy Overall Results Summary

Platform	DOD Cycle	CILCC Cycle	Test Objective	Met Objective?
Conventional	2.4	6.5	20% Increase	Yes
Hybrid	4.2	7.5		
Hybrid Percent Improvement	75%	15%		

ATC applied statistical analysis to the fuel economy data to confirm significance of the results. Table 6-4 presents a summary of the analysis. None of the 99 percent confidence values overlapped, confirming the statistical significance of the results.

Table 6-4. Statistical Analysis Results for the Utility Truck Testing

	Parameter	Conventional	Hybrid
DOD Cycle	Average Economy Value (mpg)	2.4	4.2
	Standard Deviation	0.1	0.1
	99% Confidence Lower Limit	2.2	3.6
	99% Confidence Upper Limit	2.5	4.8
CILCC Cycle	Average Economy Value (mpg)	6.5	7.5
	Standard Deviation	0.1	0.1
	99% Confidence Lower Limit	6.3	6.8
	99% Confidence Upper Limit	6.8	8.1

6.1.3 Refuse Truck Noise Measurements

Overall, the hybrid refuse truck noise was comparable, or higher than conventional truck noise with one exception. The exception was in-cabin noise measured during acceleration. Table 6-5 and Figure 6-2 show the in-cabin noise levels, and the in-cabin improvement for the acceleration mode.

Table 6-5. Refuse Truck In-Cabin Noise Levels (dBA)

	Static	Acceleration	Deceleration	Constant Speed
Conventional	71	81	72	76
Hybrid	71	77	74	77
% Change	0%	-39%	+32%	+12%
Objective Met?	No	Yes	No	No

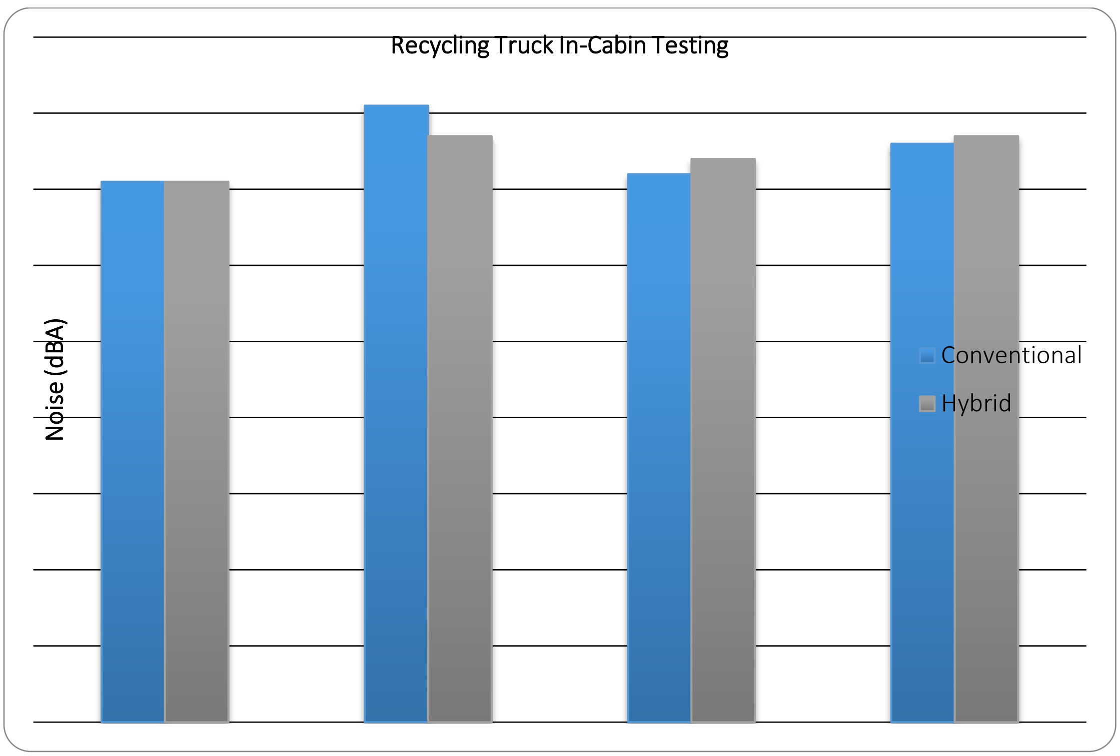

Figure 6-2. Refuse Truck In-Cabin Noise Levels: Conventional vs. Hybrid

While the results indicate higher external noise levels for the hybrid refuse truck, there appears potential for improvement. Indoor noise levels are lower due to the cabin enclosure and insulation, as well as position of the HLA system. Similarly, outdoor noise levels could also be potentially improved through further insulation or design changes.

6.1.4 Utility Truck Noise Measurements

ATC and NAVFAC EXWC conducted noise testing on the utility trucks for the same driving modes (i.e., with 10 mpg, 20 mph, and 25 mph speed points) as with the refuse trucks. Testing included acceleration, deceleration, and constant speeds. Noise characterization also included static testing with the trucks at idle (Figure 6-3). As with the refuse truck testing, receptor locations included both in-cabin and outdoor microphones.

Figure 6-3. Photo of Personnel Collecting Perimeter Noise Measurements. (photo by Chris Shires, ATC)

Table 6-6 presents results of in-cabin testing. The hybrid demonstrated lower in-cabin noise levels in the static and accelerating modes. This appears due to the electric motor's peak shaving effect during truck accelerations, and engine-off operation during the PTO mode. Hybrid utility truck noise was significantly higher than the conventional truck for deceleration and constant speed modes. This is likely due to the hybrid system's regenerative braking system.

Table 6-6. Utility Truck In-Cabin Noise Testing (dBA)

	Conventional	Hybrid	Hybrid Improvement	Objective Met
Static	66	60	49%	Yes
Accelerating	77	73	39%	Yes
Decelerating	64	68	-71%	No
Constant Speed	66	69	-42%	No

Table 6-7 shows outdoor noise levels for both utility trucks. In contrast with the in-cabin measurements there was no significant improvement during acceleration testing. As expected, the hybrid was substantially quieter for idling operations as the hybrid system supplies power to the PTO, allowing shutdown of the conventional engine.

Table 6-7. Utility Truck Outdoor Noise Testing (dBA)

	Conventional	Hybrid	Hybrid Improvement	Objective Met (20% Improvement)
Static	85	70	83%	Yes
Accelerating	80	81	-12%	No
Decelerating	70	74	-55%	No
Constant Speed	74	76	-23%	No

6.1.5 Noise Monitoring Summary

In summary, the noise benefits for both the refuse trucks and the utility trucks were limited. Neither the hybrid refuse truck nor the hybrid utility truck reduced noise across all modes of operation as compared with the baseline trucks. Both hybrid platforms provided in-cabin benefits during acceleration testing. The hybrid utility truck provided a clear benefit in the engine-off PTO mode. Both hybrid systems increased noise during deceleration mode tests.

6.2 SITE TESTING ASSESSMENT

6.2.1 Refuse Truck Site Testing

The project team held a site kick-off event with the NAVFAC Northwest operator and service team at NBK Bangor WA from February 7-10, 2011. Following the kick-off event, the trucks were in a non-operating status while the manufacturer investigated a solution for side loader issues. The manufacturer identified a solution in November 2011, and completed subsequent fixes in February 2012. Trucks launched into service in March 2012.

March 1, 2012 – Start of Data Collection (Telogis)
June, 15 2012 – Hybrid truck moved to Naval Air Station Whidbey Island WA
September 30, 2012 – End of Data collection

6.2.2 Vehicle Operations Summary

A closer look at truck operations indicates substantial differences in duty cycles over the test period. During the first three months, the hybrid truck mileage was four times higher than the conventional truck. Management corrected the disparity by sending the hybrid truck to Naval Air Station Whidbey, which led to achieved monthly mileage and average speeds comparable to the conventional truck. Figure 6-4 shows a plot of the month-to-month mileage for both trucks.

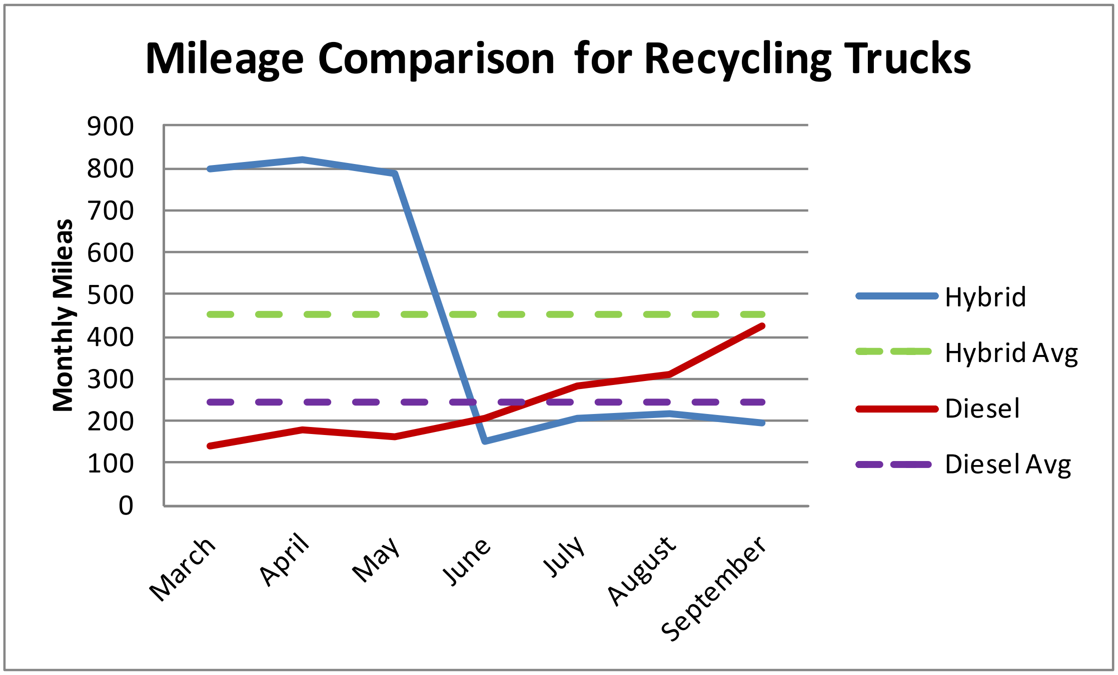

Figure 6-4. Mileage Comparison for Refuse Trucks

Service and Maintenance

Refuse trucks' experienced extended downtime due to incompatibilities with the lift units and the tote containers. Downtime was not related to the hybrid technology. Once deployed into service, the refuse truck chassis and power trains presented no significant maintenance or operational issues. Upon inspecting the trucks one year after the launching into service, the trucks were reported to be in excellent condition with no maintenance required on the chassis or power train.

Brake Wear Evaluation

Table 6-8 presents a brake wear analysis based on the difference between final measured thickness, and initial specification thickness. This data indicates the conventional truck brake linings wore at four times the rate of the hybrid trucks. For a severe duty cycle, replacement intervals would be annual for the conventional truck and every four years for the hybrid trucks.

Table 6-8. Brake Wear Evaluation on Conventional and Hybrid Refuse Trucks

	Baseline Thickness (in.)	Thickness at 18 Mos. (in)	Odometer	*Est. Wear	Mileage Specific Wear Rate (in./100k mi)	Minimum Lining Thickness (in.)	Estimated Brake Changes per 100,000 miles
Conventional	1.00	0.75	3,076	0.250	8.13	0.25	8
Hybrid	1.00	0.875	6,721	0.125	1.86	0.25	2

*Wear assumes an initial baseline thickness of one-inch.

6.2.3 Drivability

Table 6-9 provides a summary of comments related to refuse truck drivability. Both refuse trucks provided comparable driving performance, and were well suited for driving on the installations' hilly roads and interconnecting highways. The operator team reported excellent driveability, with the only comment related to the strong regenerative braking. The heavy drag of the HLA system is more severe than required for the mild duty cycle.

Table 6-9. Drivability Comments for the Hybrid Refuse Truck

Mode	Drivability Comments
Accelerations	Truck has sufficient power when accelerating from a signal stop or highway onramp.
Coasting	Regenerative braking is more severe than needed for the mild duty cycle routes.
Grade-Ability	Trucks have sufficient power to climb hills in and around NBK.
Stopping	Brake lights should illuminate for safety purposes.

Ease-of-Use

With the exception of the regenerative braking, the hybrid hydraulic system is transparent to the driver. Operator training on the braking system requires a brief awareness training session of approximately one hour. Operators will adjust to the regenerative braking after several hours of driving that includes repeated stopping.

6.2.4 Summary

From the truck operator perspective, the hybrid hydraulic system met acceptance criteria, achieving drivability and ease-of-use criteria. Service team reported no issues on the trucks or power-trains with respect to maintainability. In regard to fuel economy, the hydraulic hybrid fell short of the performance objective. By all indications, this is due to the mild drive cycle that results in trivial energy recovery by the regenerative braking system. The mild cycles generally extend to DOD's greater non-tactical heavy duty fleet, suggesting the hydraulic hybrid technology will realize limited benefits for DOD's non-tactical community.

6.2.5 Utility Truck Site Testing

Upon the completion of the track testing task, the project team delivered the trucks to Naval Station San Diego where they were launched into service following a kick-off meeting and training event. Following are highlights of the site testing.

Ride-Along Observations

Operator concerns included ride quality, acceleration performance, and transmission shift quality. Driving over bumps caused excessive movement without sufficient damping. The hybrid truck displayed poor acceleration from a stop, lack of uphill power, and abrupt shifting during downhill driving.

Operator Surveys

Both the conventional and hybrid utility trucks rated consistently for aspects including engine starting, braking quality, low speed maneuverability, deceleration/coasting, bucket/boom operation, hydraulic power, noise levels, and in-cab ergonomics. The hybrid scored consistently lower on acceleration in both of the surveys with ratings of 1.5 and 2. After the hybrid truck received a software update in August 2011, its ratings improved from a "worse" (2) rating to a "good/great" (4.5) rating in pulling grade and transmission shift quality.

Reliability

Table 6-10 presents the availability data throughout the site-testing period: July 2011 to March 2012. The data is based on labor hours charged to each service event. The conventional and hybrid utility trucks demonstrated availabilities of 99 percent and 98 percent, respectively.

Table 6-10. Availability of the Conventional and Hybrid Trucks (Percent)

	Jul 2011	Aug 2011	Sep 2011	Oct 2011	Nov 2011	Dec 2011	Jan 2012	Feb 2012	Mar 2012	Average
Conventional	100	90	100	100	100	100	100	100	100	98.9
Hybrid	95	95	95	95	100	100	100	100	100	97.8

Maintainability

Service mechanics gave a rating of "good" for truck maintainability and serviceability. Hybrid utility truck design was identical to the conventional utility truck with the exception of the added hybrid system. Maintaining the hybrid truck was straightforward with minimal issues during the demonstration period.

Brake Wear

Brake pad thickness was measured on the right front wheel for both trucks. At the conclusion of the project, brake lining thickness for the hybrid truck was 0.38 in or 9.65mm as compared with 0.365 in or 9.27mm for the conventional truck. This is a 36 percent reduction in wear based on the 0.75" specification thickness for the factory brake linings.

Automated Data (Telematics System)

Coastal Utilities team launched the utility trucks into service in June 2011. Data collection began in July 2011 and continued through March 2012. On average, the trucks drove between 18 and 35 miles per day. The hybrid truck logged twice the miles as the conventional truck through the test period. This was due to the hybrid's frequent trips to Marine Corps Air Station Miramar.

Fuel Efficiency

Figure 6-5 is a plot of automated mileage and fuel data captured from the telematics system. There was only one month (December 2011) where the hybrid economy improvement dropped below the 20 percent performance objective. On average, the hybrid demonstrated a 32 percent improvement in fuel economy over and above the conventional truck.

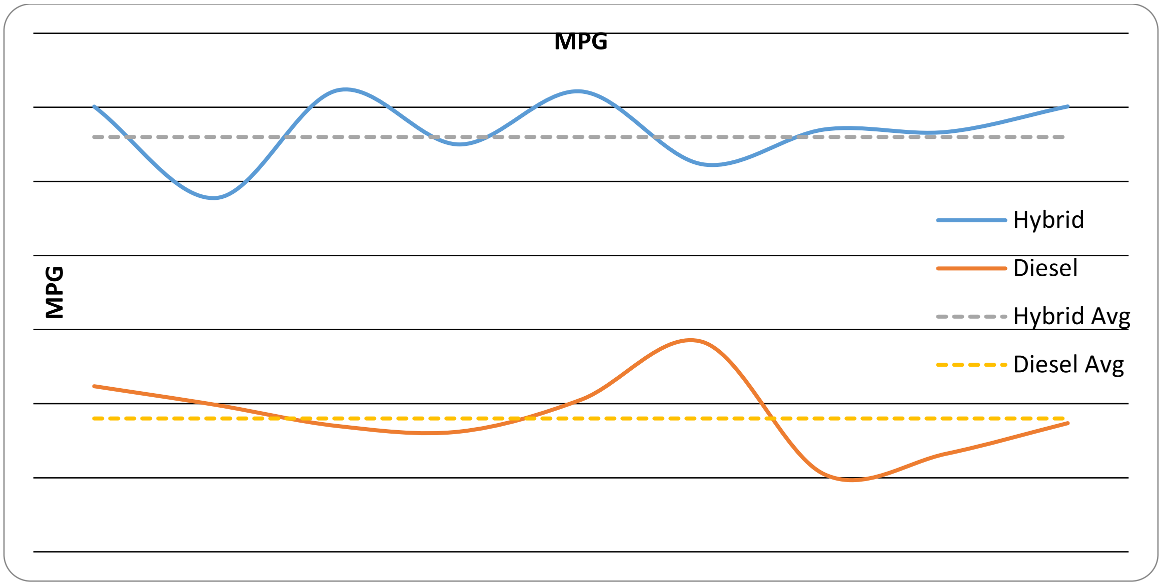

Figure 6-5. Fuel Economy Comparison for Conventional and Hybrid Utility Trucks

6.3 PERFORMANCE ASSESSMENT SUMMARY

THIS SECTION SUMMARIZES TEST RESULTS AND CONCLUSIONS FOR EACH HYBRID PLATFORM.

6.3.1 Refuse Truck Test Summary

The refuse truck equipped with the hybrid HLA system failed to meet the critical performance objective for fuel economy. This result is not related to the hybrid system, but is due to the mild driving conditions characteristic of most non-tactical truck applications on DOD installations. The project team feels the same truck, if placed in a severe duty cycle, would yield entirely different results. The hydraulic hybrid also fell short of the noise reduction objective for outdoor noise, showing a 20 percent increase in noise rather than a reduction. Recommendation is for fleet management to further investigate candidate cycles and next generation hydraulic hybrid systems prior to finalizing procurement plans.

6.3.2 Utility Truck Test Summary

The hybrid utility truck successfully achieved four of six performance objectives, including fuel economy, noise, maintainability, and ease of use. The truck fell short of the drivability and brake wear objectives. Operators expressed drivability characteristics as a considerable annoyance. The project team concludes drivability will improve with further refinement and engineering for next generation trucks. As with drivability, brake wear can be reduced with further optimization to meet the objective. Hybrid electric utility truck is considered acceptable by the project team, with the recommendations that purchasing agents specify the driving performance requirements for the intended application.

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7.0 COST ASSESSMENT

This section provides an economics review for the heavy hybrid technologies demonstrated under this project. Economics are based on anticipated non-tactical applications and benefits for DOD vehicle fleets for domestic public works applications. From a cost/payback perspective, this type of application is conservative. Non-tactical fuel delivery logistics are routine. Tactical users will realize improved economics due to the fuel savings and other enhanced capabilities.

7.1 COST MODEL

Cost assessment for public works fleet applications is relatively straightforward. This assessment estimates overall return on upfront investment by subtracting value of the beneficial features from the hybrid's cost premium. Paragraphs below discuss assumptions:

1) Hybrid Premium. Assumes commercial market development, and 40 percent reduction in hybrid system cost from baseline 2013 costs.[i]

2) Fuel Savings. Trucks will improve fuel economy by 20 to 30 percent for the hybrid hydraulic and hybrid electric systems, respectively.

3) Operation and Maintenance. Hybrid trucks will realize reduced fueling labor, reduced brake wear, reduced oil changes.

4) Indirect Environmental Benefits. Hybrid systems will mitigate global warming emissions, engine noise emissions, and petroleum processing and delivery emissions.

5) Capability and Energy Security. Hybrid hydraulic systems improve power and acceleration performance. Hybrid electrics provide enhanced PTO capability.

The project team coordinated with each demonstration site in order to monitor and collect operations and maintenance data to assess cost of the hybrid systems. The team also reviewed available market studies to the project future costs of mass produced hybrid trucks.

7.2 COST ANALYSIS AND COMPARISON

This section evaluates cost payback for both the recycling and the utility trucks. Evaluations are specific to each platform and application. Technologies differ in the way they recover and expend energy, and subsequent payback is reliant on the specific use application.

Refuse Trucks

For this demonstration, the hydraulic hybrid saw no fuel economy improvements. This was due to the relatively mild duty cycle. Given this result, the cost assessment assumes a severe duty cycle that includes low-speed pickups/deliveries for a minimum of six hours per day. Note this initiative still requires further testing to validate fuel economy performance under actual use conditions. Table 7-1 presents a lifecycle cost assessment for a hybrid refuse truck.

Table 7-1. Cost Analysis for Hydraulic Hybrid in Severe Duty Cycle Scenario

Hybrid Program Costs				Indirect Environmental Activity Costs		12-Year Hybrid Cost Total
Capital Equipment and Infrastructure		Operation & Maintenance[1]				
Activity	$	Activity	$	Activity	$	
Hydraulic Hybrid System Cost[1]	$30,000	Reduced Fuel Use (20% Less Consumption) (4,668 gal saved @ $5.00/gal)[2]	-$23,333	Air Emissions 56 fewer tons of CO2 over truck life [7]	-$1,400	
		Fueling Time and Frequency (46 hours less labor)[3]	-$3,500			
		Avoided Delivery to Fuel Storage Tank (one per year)[4]	-$467			
		Avoided Labor for Brake Maintenance[5]	-$1,650			
		Training Event for Operators, Service Crew[6]	N/A			
Totals:	$30,000		-$29,223		-$1,900	-$1,123

Assumptions:

1. Purchases occur in the 2015 to 2020 timeframe, and hybrids are in full commercial production.
2. 12-year life cycle, 7,500 miles annual use, six mph average speed, multi stop duty cycle. Conventional truck fuel economy is 3 mpg.
3. Conventional refuse trucks fill every 50 gallons or 150 miles, or 46 events per year. Hybrid trucks improve fuel economy by 20 percent, avoiding seven fill events annually, or 96 per lifetime. Fuel events require 30 minutes of the operator's time, at $75 per hour.
4. Hybrid trucks will reduce a single delivery of 5,000 gallons of fuel to the station. This avoids four hours' effort total for driving, fueling, and administrative operations, at $75/hr.
5. Conventional truck brake lining replacements occur once every 12,000 miles. Hybrid truck brake lining replacements occur every 50,000 miles. This results in six fewer replacements over the hybrid truck lifetime. Each service visit requires three hours of labor at $75/hour and $50 for parts.
6. Hydraulic hybrid system requires no substantial training beyond basic orientation by the local distributor. Service teams are familiar with hydraulic lift systems.
7. Diesel fuel results in 22.4 lbs. GHG/gallon of fuel. GHG market value is $25/ton.[ii]

The hybrid equipped refuse truck is not cost effective for the mild duty cycles as tested. Also, DOD appears to have few promising severe duty applications that would substantially benefit from the technology. A hypothetical scenario where the truck would be cost effective includes six hours of daily use at low average speeds and multiple stops. Under this scenario, the return on investment is approximately $4/mile for every mile above 90,000 miles.

Utility Trucks

Performance test results indicate the hybrid electric utility platform will be economically viable with further market development. Integration into the military non-tactical fleets over the next four to eight years can improve the services' energy security profile for medium and heavy platforms. Table 7-2 presents a lifecycle cost assessment.

Table 7-2. Cost Analysis for Hybrid Electric under Severe Lift Cycle Scenario

Hybrid Program Costs				Indirect Environmental Activity Costs		12-Year Net Cost for Hybrid
Capital Equipment and Infrastructure		Operation & Maintenance[2]				
Activity	$	Activity	$	Activity	$	
Hybrid Electric Cost[1]	$37,000	Reduce Fuel by 6214 gal @ $5.00/ gal)[2]	-$31,071	(Reduce CO2 Emissions by 73 tons over truck life)[8]	-$1,554	
		Fueling Time and Frequency[3]	-$4,661	Increased Productivity (1% increase)[9]	-$6,300	
		Avoided Brake Maintenance[4]	-$550			
		Avoid One Oil Service per year at $320)[5]	-$3,520			
		Battery Replacement[6]	$4,800			
		Training for operators, service team[7]	$3,000			
Totals:	$37,000		($32,002)		($7,854)	($2,856)

Assumptions:

1. Operating Scenario: 12-year truck life, commercial production volumes for hybrid electric systems. Trucks drive 7,500 miles annually, and operate 3 hours in the PTO mode (daily).
2. Fuel Savings: Conventional utility trucks consume 1,770 gallons of fuel annually, including 1,154 gallons for driving (7,500 miles at 6.5 mpg) and 616 gallons for PTO operations (700 hours at 0.88 gph). Hybrid truck fuel consumption is 1,252 total, including 1,000 gallons for driving (7,500 miles at 7.5 mpg) and 252 gallons for PTO Operations (700 hours at 0.36 gph).
3. Fueling time and Frequency: Avoided fueling estimate considers filling the tank when fuel level drops to one-quarter full. The hybrid avoids 124 events, or 62 labor hours (assuming 30 minutes of operator time per event) and $4,650 in labor assuming $75 hourly rate.
4. Brake Maintenance: Service events occur every 15,000 miles (or 3-years) for the conventional truck, and every 20,000 miles for the hybrid truck. Service incurs four hours' labor per event, at $75/hour. Parts cost is $50.
5. Oil Service: Assumes one service event every 550 hours. The hybrid truck avoids 562 hours per year of engine operation through engine-off PTO, or one oil service event per year. Each event assumes 3 hours in labor and $95 for replacement parts and consumables.
6. Battery Replacement: Assumes replacement of a 6 kilowatt-hour battery pack at a cost of $800/kilowatt-hour.
7. Training: Assumes 4-hour training event for service team, and 2-hour training event for operators.
8. GHG Production: Assumes 22.4 lbs./gal of diesel, and indirect benefit of $25/ton GHG.
9. Productivity: Engine-off PTO increases productivity by 1% above the conventional truck due to enhanced operational capability (i.e., improved communications between ground and work crew).

In summary, the hybrid electric utility truck is cost effective for operating scenarios including a minimum 7,000 miles per year of driving, and three hours of daily PTO use. Simple payback will occur over a 12-year life cycle assuming the above scenario.

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8.0 IMPLEMENTATION ISSUES

The hybrid utility truck fell short of meeting two objectives, drivability and brake wear. Poor drivability (specifically accelerations and hill-climbing ability) is critical to ensuring broad scale acceptance by the users. This symptom is related to the early commercial nature of the technology, and will be resolved through further manufacturer refinement and engineering. Reduced brake wear is less critical, but will help agencies realize better return on investment. Feedback to the hybrid industry through the non-tactical working group will help improve the brake wear objective.

Fleet managers are the responsible entity that must integrate heavy hybrid technology into the vehicle fleets. The $50K to $70K cost premium is a primary administrative hurdle to heavy hybrid integration. The decision to purchase hybrid technologies means the agency receives fewer trucks at a higher cost. With incremental costs prohibitively high, the industry must see discounts or other incentives. Coordination with industry through the non-tactical military working group will help identify and distribute incentives.

For the military, planning is a critical first step. Identification of the most beneficial applications will help achieve economic payback. Recommended initial steps for DOD include 1) characterize inventory subject to high use or abusive cycles; and 2) pair hybrid technology and application sets promising the greatest benefit. The first step requires a service-wide effort to capture operator data and identify inventory that offers the greatest benefit. The US General Services Administration also has data acquisition technologies on schedule that will assist with duty cycle characterization.

Training is the other item that is critical to successful technology implementation and integration. Fleets will realize greater support, and improved chance of user acceptance, if operators understand operating concepts and best operational practices. Also, in the interest of safety, all service and maintenance training should accompany delivery of all new hybrid trucks. The high energy systems are potentially hazardous and could result in injury or death unless fleet management takes proper precautions and ensures mechanics are trained for servicing the energy storage systems. While hybrid systems will require minimal or no attention, there are scenarios where the service team must know proper procedures to work on or around these systems.

Accidents involving hybrid platforms also present new challenges and potential hazards to emergency responders and vehicle operators. Personnel must have training on accident response procedures including system shutdown or isolation procedures. Battery packs and high pressure accumulator systems present potential for electrocution, toxic gas inhalation, or overpressures if compromised by fire or physical damage. In the event that accidents involving the hybrids, emergency response crew must have more than an awareness of the high energy hazards of the hybrids. Crew must be trained to watch for the hybrid labels and be instructed in the procedures to de-energize electric or gas lines that are compromised and present a hazard. Project team recommends circulation of fact sheets to appropriate claimant commands and within the agency to promote awareness.

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9.0 REFERENCES

[i] National Research Council, Transportation Research Board, "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles", ISBN: 0-309-14983-5.

[ii] Interagency Working Group on Social Cost of Carbon, "United States Government Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866", February 2010.

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APPENDIX A TITLE

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